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A NORMATIVE MODEL FOR ORGANIZATIONS

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ABSTRACT

A review of conceptual and formal models suggests that organization structure can be described by sets of tasks and resources upon which are defined several types of relations, such as, task interdependence, coordination policy, reward structure, information flows, and informal coalitions. This paper translates the notions of task, resource, and hierarchical coordination into an empirically testable model of organization. The simplest form of the model constructs a least cost hierarchy to provide the coordination manpower required by a given network of interdependent tasks. A more elaborate form of the model treats resource assignments as variable and computes coordination requirements as a function of task uncertainty, skill mix, and type of task interdependence. The paper is concluded with a brief plan for a field test of the model.

CONTENTS

1. Overview

Managers and management theorists have long discussed how a firm ought to be organized. But this debate had little substance until the theorists developed conceptual models, which empiricists then used to explain differences in organizational performance. Of late, research on structure has been guided by the desire to construct and refine a contingency theory of organization. Such a theory is merely a list of important technological and market variables, plus a catalog of organizational forms which are appropriate for specified configurations of these variables.

Logically, the next step is to devise a unified theory, ie., an objective function and a set of relations among variables, which "explain" why a particular structural solution is found in a given environment. Recent studies (Galbraith, 1969; Thompson, 1967) have laid the basis for a unified theory. Our intent is to incorporate some of these ideas into an empirically based model for coordinating tasks and resources at least cost.

Because organizations are so very complex, it is necessary to limit strictly the number of variables considered. In concentrating upon tasks and resources, we consciously exclude key structural variables, e.g., information flow and reward system. More important omissions are the psychological variables which would permit a better match between individuals and the roles defined by a particular structure.

As the first step towards model formulation we review previous work in order to idenfity important classes of structural variables and pinpoint the kind of model best suited to our purpose. We next suggest a way to break apart the problem of structural design, develop a model for one piece of the problem, and conclude the paper with a plan for empirical verification.

2. A Review of Formal and Conceptual Models

Three categories of research will be considered -- empirical studies, conceptual models, and formal models. However, since excellent empirical summaries are available (Lawrence and Lorsch, 1967; Galbraith, 1969) only the literature on models will be reviewed in detail.

Empirical Studies

Because empirical research on structure is just beginning in earnest, simple models suffice to summarize what is now known. For example, Lawrence and Lorsch employ a three variable scheme to summarize their own results and explain older findings. In their view, uncertainty in a firm's environment forces the firm to establish subunits which are differentiated along task and interpersonal dimensions. Obviously, the greater the differentiation among subunits, the greater is the coordination required among subunit activities. Galbraith measures this coordination in terms of the amount of information the organization must process. His review of both empirical and theoretical work suggests that principal determinants of information load are task uncertainty, and the number and interdependence of decision elements.

In contrast to the limited empirical research on structure, the literature on organization abounds with conceptual models, some quantitative, some whose constructs and relations are imprecisely defined. We shall briefly examine four examples of each type.

Quantitative Conceptual Models

Most of the quantitative models can trace their origins to the economic theory of the firm. According to this model, the firm selects a particular technology and then chooses resource inputs and product outputs in a way

to maximize profits. Moreover, this model can be extended to cope with any degree of input, output, or technological uncertainty so long as one can specify all the policy alternatives and their consequences. The choices made determine the broad outlines of the firm (in the sense that the input-output characteristic determines the "form" of a filter) but say nothing explicit about how the firm ought to be organized.*

If the economic model of the firm has so little to contribute to a structural model, then why mention it at all? For two reasons: first, all normative models, including the one developed below, have one feature in common with the model of the firm -- using a precisely stated objective function to choose one from a set of well defined policy alternatives. Second, this very crispness of structure is so compelling, and seductive, that one must be on his guard not to use the idea of known alternatives when the process being modelled has to generate alternatives prior to choice.

The extension of information theory to decision making is a prime example of an application where the economic model may be inapplicable. Ackoff (1958, p. 218) based such an extension on

> a formal definition of behavioral elements in an individual's "purposeful state": specifically, these elements are his objectives, his valuation of each objective, his possible courses of action, the efficiency of each course of action in achieving each objective, and his probability of choice for each course of action.

Practically everyone would agree that decision making is the core management activity and thus a likely stone on which to build a structural model of organization. But most firms must make non-routine decisions (Simon, 1965)

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*In fact a statement about organization structure is tacitly made if input, technological, or output alternatives are implicitly associated with certain structures. Thus, structure is almost always a confounding variable in any attempt at empirical verification of the theory.

for which alternatives and even objectives must be generated in the course of the decision (Soelberg, 1967; Cyert and March, 1963). Thus, firms where non-routine decisions account for a large share of the information processing (e.g., firms investing heavily in R & D) are not suited to a structural model employing information as a variable since one cannot measure information unless all actions and consequences are known. However, an information-based model does not even seem practical for a routine decision making context because of the prodigious amount of data required. A little later we shall have the opportunity to examine some structural models which apply information-theoretic notions to very stable task environments.

Modern control theory provides a third candidate for a quantitative language to be used in modelling structure. An interesting illustration of this approach is Mesarović, Sanders, and Sprague's (1964) characterization of an organization as a multi-level, multi-goal system. Like simple control theory, the multi-level, multi-goal approach depicts a system as a network of interlinked components (activities), where each component is described by a function relating its input to its output. But Mesarović's model is apparently unique in the asymmetrical nature of the input-output functions defining goal behavior. Let us permit the authors themselves to explain this asymmetry in terms of the definition of level (p. 498):

> Consider two goal seeking units G_{ik} and G_{jl} . . . . The goal seeking unit G_{ik} will be considered to be on a higher level than (have a higher priority of action over) G_{jl}, $(i>j)$, if the decision made by G_{ik} directly affects the goal seeking activity of G_{jl} while the decision made by G_{jl} might influence G_{ik} only indirectly via the performance of the over-all system.

Although the authors apply their theory to a simple 2-level, 3-goal production example, we feel that this model has limited usefulness because of the difficulty in collecting the empirical data needed to define all the input-output functions. As we shall see below, man-machine simulation may provide a way around this problem.

Graph theory is the final type of quantitative language we wish to consider. In abstract terms, a graph is simply a set of points on which are defined a relation (several different relations, if you wish!). Harary, Cartwright, and Norman (1965) have studied general mathematical properties of graphs useful in portraying social structure. But we shall limit our remarks to papers by Oeser and Harary (1962,1964) because of the direct relevance of their ideas for models of organization structure. They consider three sets of points -- people, positions, and tasks -- upon which are defined five kinds of relations -- personnel assignment, task responsibility, power, liking, and communication. In any complete theory of structure, one would want to consider other sets and relations (e.g., sets of resources and attributes of task output; relations describing reward structure and formal information flows). However, the form of the model is most attractive because it is well suited to meaningful organizational "variables" like task assignments and communication, which can be operationally defined, c.f. Allen,(1969). Oeser and Harary have used graph theory descriptively, but if an objective function were chosen, it would be a simple matter to use this language normatively.

Unfortunately, in spite of all its attractive features, graph theory does have a couple of limitations. First, it is ill-suited for modelling dynamic phenomena within an organization, e.g., the organizational response

to a swift economic downturn, a severe interruption in production, a sudden infusion of new blood, or a precipitate change in a competitor's product offering. Second, so far as normative modelling is concerned, the problem must be formulated so that it is computationally feasible to examine all the combinations of nodes (or arcs) which define potentially optimal solutions. The model developed below may have overstepped this bound. We hope not.

This concludes our sampling of quantitative languages possibly useful in modelling organizational structure. Before discussing the few serious models which have been published, let's pause to see whether conceptual models offer any clues about formal treatment of structure.

Non-Quantitative Conceptual Models

Probably the richest conceptual model we have is Cyert and March's (1963) Behavioral Theory of the Firm. It is an ingenious process model organized around the notion of a computer program and synthesizing concepts from administrative theory, the psychology of problem solving, human communication, economics, game theory, and mathematical programming. The theory itself consists of three categories of variables -- goals, expectations, and choice -- and four relational concepts -- quasi-resolution of conflict, uncertainty avoidance, problemistic search, and learning. However, upon closer examination, we discover that the variables are not easily operationalized and that the relational concepts are, for the most part, insightful descriptions of search and choice phenomena; for example, "problemistic search" means that one begins with the simplest plausible model of causality and then attempts to solve the problem by piecing together solutions to previous problems.

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* To cite one example, we contrast the important role of "slack" in the theory with the scarcity of published research on this variable.

In a word, Cyert and March have given us a language useful in talking about the process of organizational decision making, but this language is not immediately translatable into a set of structural variables.

In contrast, Miller and Rice (1967) have developed a conceptual model which they have, in fact, applied in advising firms about structural changes. Key elements of the model are activities and resources which are combined into task systems performing the import, conversion, and export processes that define the nature of the enterprise. A maintenance system procures and maintains the human and material resources required by a task system, and a regulating system coordinates the activities in the other two systems.

Moreover, there are a number of constraints which are important in any production system employing humans. Each individual is a member of many overlapping role sets and he must attend, more or less, to the expectations of each role sender. Consequently, employee satisfaction and deprivation is determined both by the capacity of the task to fulfill individual needs and by the quality of his interpersonal relations inside and outside his task group. Note that individual satisfaction is one aspect of the design problem which we have consciously chosen to ignore. In principle, task closure and role set could be incorporated into a model, but the resulting formulation would be analytically intractable, even for small organizations.

Miller and Rice outline a four-step process for using their model to analyze organization structure: 1) identify the primary task, i.e., the task the organization must perform if it is to survive; 2) identify the primary import-conversion-export process; 3) place the boundaries of the

task systems at points of sharp discontinuity in this process; and 4) verify that each task system has its own maintenance and regulatory system, and that the flows across every system boundary are coordinated by one regulatory system.

Although Miller and Rice have not stated a set of operational rules for applying their design formula, we suspect that such rules could be devised. Moreover, this would be a worthwhile endeavor because task, maintenance, and regulatory systems are concepts highly relevant to the problem of structural design. Indeed, we are rash enough to assert that in any serious structural model of an organization, one should be able to identify these three subsystems.

Like Miller and Rice, Thompson (1967) has a systemic view of organization. But Thompson goes farther than any other writer in suggesting how particular structural features are caused by market characteristics and by the pattern of work flow imposed by technology. He develops many intriguing propositions about organizational rationality, the pursuit of power, the impact of technological structure on growth patterns, and the influence of environment upon the structure of units at the periphery of an organization. More interesting to us is his identification of three kinds of interdependence within the task system: pooled interdependence occurs when activities share the same resource; sequential interdependence arises when one activity provides input to another; and reciprocal interdependence is created when each activity both provides input to and receives inputs from other activities. Moreover, Thompson suggests that one mode of coordination is appropriate for each relationship -- standardization for pooled, plans for sequential, and mutual adjustment for reciprocal interdependence. Observing that

mutual adjustment is the most costly form of coordination and standardization, the least costly, he proposes a plausible design rule: begin by grouping all reciprocally interdependent activities; absorb sequential interdependence at higher hierarchical levels; and finally, standardize operations within the remaining pooled activities.

The validity of Thompson's design heuristic is a matter for empirical test. However, his categorization of interdependence has enough face validity to influence the formulation of any model of the task system.

Galbraith's (1969) model of organization is a synthesis of the information processing concepts developed by the Carnegie School; the structural theories of Thompson and other open systems theorists; and the recent empirical works by British and American sociologists. As we noted above, the present development of information theory does not permit empirical measurement of information processing capacity in organizations which do a great deal of non-routine problem solving. Perhaps this measurement is feasible for organizations using a very predictable technology and serving a very predictable market.

However, for the moment let us set aside the measurement issue in order to review the kinds of information processing mechanisms which Galbraith sees firms using. Rules and programs are the least costly form of coordination, and thus, are the first mechanism used. A managerial hierarchy of non-routine problem solvers is created to deal with exceptions to the rules, and this hierarchy grows until the combination of rules and hierarchy becomes too expensive to administer. Planning is then introduced to relieve the hierarchy. As the amount of information to be processed continues to grow, the organization begins to employ some of the following mechanisms: it 1) permits the accumu-

lation of slack resources via buffer inventories or underutilized equipment; 2) creates self-contained activities by reducing the number of specialties or duplicating facilities; 3) enhances the capacity of the hierarchy through automation or by adding staff assistants; 4) develops a network of lateral relations, which range in complexity from direct contact to formal integrating departments or a matrix organization. This is a pretty complete list of the policy variables available to a design not concerned with individual satisfactions. Reward structure seems to be the only major omission.

Formal Normative Models

We now have a fair idea of the kinds of concepts and languages theorists have developed for studying organization structure. Before attempting a synthesis of our own, let's review the literature on formal normative models. It will not take long. A fairly extensive search of the last ten years of publications revealed only six models of interest to us.

The first group of models are largely elaborations of Jacob Marschak's (1954, 1955) economic theory of organization. As the first step toward understanding more complex structures, Marschak (1955) chose to analyze a team whose common reward is a function of the decisions made by individual members. Although the expository examples used were very simple, they contained many of the characteristics of more complex organizations. Stated concisely, the complete team problem is to determine the communication network and team decision rule which yield the maximum net payoff in the face of unknown, but describable states of nature, known costs of observation and communication, and a payoff function which rewards coordinated action and penalizes uncoordinated action. Marschak solved his simple examples by computing the best team decision rule for each communication pattern and then selecting the pattern whose rule had the highest payoff. Radner (1959) formulated the same problem as a linear program for the case of two observation variables and two decision variables. McGuire (1961) applied these notions to the study of centralized, decentralized, and mixed communication patterns within a salesforce serving a wholesale bakery. An examination of the criterion function may help to clarify the structure of the problem. Define

y_i~the demand parameter in the i^{th} market, assumed to be prohibitively expensive to observe;

z_i~a quantity related to y_i, but more observable;

w~the production capacity, assumed to be known;

$\underline{x} \equiv (z_1, \ldots z_n; y_1, \ldots y_n; w)$, a vector describing the state of the world;

$\eta_i(\underline{x})$~the information available to the i^{th} salesman; where

$\eta_i(\underline{x}) = \underline{z}$ characterizes a centralized structure, and

$\eta_i(\underline{x}) = z_i$, a decentralized structure;

$\alpha_i[\eta_i(\underline{x})]$ ~ the order placed by the i^{th} salesman;

$k(\underline{\eta})$ ~ the cost of the information structure;

Then McGuire's problem is to choose the N action functions $\{\alpha_i[\eta_i(\underline{x})] \geq 0\}$ to maximize the expected profit of the firm:

$$E\left\{ \sum_{i=1}^{N} R_i(\alpha_i, y_i) - C\left(\sum_{i=1}^{N} \alpha_i, w\right)\right\} - k(\underline{\eta}) \quad ,$$

where R and C are, respectively, revenue and production cost. McGuire spent the bulk of his time deriving the optimal decision rule for various combinations of price uncertainty, demand uncertainty, and the shelf life of bakery products. He devoted little effort either to comparing the costs of the various information patterns or to speculating about how his results might be used in evaluating the structure of real organizations.

In a parallel development, Thomas Marschak (1959) has explored the dynamic behavior of a team which observes the world periodically, processes the observed information several times, and then submits a team decision before the next scheduled observation. Like McGuire, he investigates centralized, decentralized, and unrestricted structures. But T. Marschak introduces a new twist by applying two criteria: 1) the degree to which the organization is "satisfied" with its decisions, and 2) the time it takes for the organization to reach a decision. In no case is the cost of communication considered.

If individual reading and writing times are small compared to computation time, the unrestricted model is best and the centralized model is worst according to criterion two. However, the fluctuating behavior of the satisfaction function makes it impossible to rank the models on the basis of criterion one.

As a summary comment on these four economic models, we note that all are limited to routine decision making situations, all are exclusively con-

cerned with production in contrast to maintenance and control, all achieve coordination via rules and lateral relations, and only T. Marschak's models permit patterns of task interdependence more complex than pooled. But for all their limitations these models do provide a useful beginning.

The two models which remain to be discussed are both simulations of fictitious organizations. Bonini's (1963) simulation of a manufacturing firm was constructed to explore a number of ideas in the information processing theory of decision making. The simulated firm was functionally organized and had five levels. Key elements in the model were centers where decisions were made; centers where information was accumulated, transmitted, or analyzed; rules applied at the decision centers; and links among the information centers. Budgets and prices were determined by decision rules which operated iteratively on aspiration levels until satisfactory performance was obtained. And each decision maker was subject to a pressure function which reflected both deficiencies in his own performance and the pressure felt by his immediate superior. Limited resources restricted Bonini to a controlled study of only eight factors, among them, the pressure function, the content of information flows, and some of the decision rules. However, the simulation is structured in a way to permit study of virtually all of the coordination mechanisms described by Galbraith plus some of the group variables discussed by Miller and Rice.

The most flexible model we have seen is the man-machine simulation, LEVIATHAN, constructed at the Systems Development Corporation in the early 1960's (Rome and Rome, 1962, 1964). A five-level hierarchy incorporating

85 human roles, LEVIATHAN simulated the Intelligence Communications Control Center, a department of the (fictitious) National Intelligence Agency. The Center's mission was to receive intelligence communiques from all parts of the world, process them, and then transmit them to the proper government agency. Each communique travelled through one of nine parallel processing lines, manned by heterogeneous machine people and supervised by successive layers of humans. The human managers could establish and administer priorities, routing rules, productivity rates, and could make individual robot reassignments. Moreover, in the event that an individual manager was frustrated in his efforts to deal with the formal organization, he could tap the power of coalitions resident in the ever-changing informal organization. As one can see, this was, indeed, a most flexible model.

A total of five runs were made with the simulation, and the duration of each run ranged from 15 to 28 four-hour days. All managers but the agency chief were graduate students. In the first run the second level managers were specialists, in the second and third they were generalists, and in the fourth run the third-level managers were specialists, thus yielding a matrix organization. It is difficult to sort out the combined effects of learning, lateral communication, formal structure, crisis inputs, and the performance reports given to the managers. However, there is evidence that lateral communication greatly improved productivity, that exception reporting was beneficial, and that a straight functional organization was the least efficient.

LEVIATHAN is an excellent example of the richness of structure afforded by a simulation. But at the same time we are again reminded how costly

it is to develop a simulation and how difficult it is to understand its behavior. In the next section, we shall propose a research strategy that combines the flexibility of simulation with the lucidity of analytic modelling.

3. Model Elements and a Research Strategy

Perusal of the languages and formal models reviewed above suggests that organization structure can be adequately described by sets of tasks and resources upon which are defined several types of relations, including task interdependence, coordination policies, a reward structure, information flows, and a network of informal coalitions. Let's take a closer look at each of these elements.

The task set includes production and maintenance activities as defined by Miller and Rice, but excludes regulatory activities which we prefer to view as a coordination relation. It would be nice if each task could be uniquely defined by one output. However, many physical outputs have a number of attributes, so the operational definition of task will surely involve an artful aggregation of outputs. Recall that an empirically significant task attribute is uncertainty, which should be measurable by comparing predicted and actual completion times during a stable segment of organization history.

The resource set is more easily defined. It consists primarily of men, material, machines, and uncommitted monies. Obviously, we intend to measure all resource capacities and usage rates in monetary terms.

Task interdependence is the fundamental relation tying tasks to one another and to resources. Assuming that the problem of task identification is empirically solvable, we shall utilize Thompson's notions of pooled, sequential, and reciprocal interdependence. Precedence relations and resource sharing should be easy to measure once one is satisfied with the task definitions. Note that the assignment of human skills to tasks contributes

in part to Lawrence and Lorsch's concept of differentiation, which is an important determinant of coordination effort.

Coordination policies are a heterogeneous set of relations taken over bodily from Galbraith, namely, rules, the supervisory hierarchy, plans, slack resources, and lateral relations. Structure was omitted because it is deemed to be subsumed under hierarchy and task interdependence. Structurally, this set of policies is a mixed bag. It ranges from an assignment of outnut targets to tasks, to rules specifying how task inputs should be combined, to the inter-task links implied by a supervisory hierarchy.

The reward structure assigns each task group supervisor an evaluation rule which is a function of the actual and expected values of the task inputs and outputs for which he is responsible. Note that "for which he is responsible" does not necessarily mean "under his direct supervision."

Our conceptual model is completed by specifying a formal network of information flows and an informal network of coalitions among supervisors. The norms of the coalition structure modify the reward functions, and the interaction implicit in the notion of coalition adds links to the formal communication system. Of course, we do not assume that a supervisor's behavior is necessarily influenced by knowledge about the performance of his own or related tasks!

Throughout the description of our conceptual model we have used language in a way that suggests an underlying graph theoretic model. Such a formulation is feasible in principle, but the size of the sets and the complexity of the relations required would render a comprehensive model intractable, to say the least. A more promising approach would be the fragmentation of the complete structure into two parts. A machine simulation would be

used to accumulate data on resource requirements resulting from a given reward structure and set of coordination policies. Then these requirements would be fed into an analytic model which could handle the nasty combinatorial problems encountered in solving for certain structural features, the supervisory hierarchy, for example. These structural features would then be fed back into the simulation to generate new requirements and the iteration would continue until consistent results were obtained.

This is not the cheapest nor the most elegant method of attack. Wisdom counsels some inexpensive reality testing as a first step. With that end in mind, we have developed a simple model and proposed a plan for its empirical verification. Tasks, resource requirements, and task precedence relations are the fundamental givens, but task uncertainty, and level of specialization are also included as parameters because it is so easy to incorporate them into the model. Model outputs are a supervisory hierarchy, an assignment of resources to tasks, and a specification of resource sizes which combine to yield minimal cost operation.

The model is developed in two parts. In section 4 we create a hierarchy to absorb known coordination requirements at minimal salary cost. In section 5 we add the effects of resource sharing and make coordination requirements an explicit function of interdependence, level of specialization, and task uncertainty. The final section of the paper outlines a 3-4 year plan for a step-by-step field test of the model.

4. Model I: Variable Task Assignments; Fixed Coordination Costs

As noted above, the organizational design problem consists of choosing "values" for a number of different variables:

-- the missions or meta-goals selected by the organization, and the products and services, production technology, and marketing strategy appropriate to these missions;

-- the task structure and kinds of resources required for operation;

-- coordination policies, including rules, a supervisory hierarchy, resource assignments, plans, slack resources, and lateral relations;

-- the reward structure for human behavior, both formal and informal;

-- the structure and content of information flows, etc.

The simplest model for design may be developed by holding all variables constant but the managerial hierarchy. Thus, in the model which follows we assume that elemental tasks have been specified and that task coordination costs have been measured. The problem is to specify a managerial hierarchy to handle a fixed amount of task coordination at least supervisory cost. To choose among hierarchies having the same supervisory cost, we require that the dollar cost of the time actually spent in coordination be minimal. The second order criterion frees time for higher level managers to find and solve problems outside the pale of task coordination.

Let us begin by specifying model elements and certain intermediate quantities used in the analysis.

Define

n^{α} ∿ the total number of tasks at the αth level in the hierarchy; the lowest level is denoted by $\alpha = 1$;

c_{ij}^{α} ∿ one half of the personnel cost of coordinating tasks i and j at level α, measured in men; c_{jj} is the full cost of handling the nonroutine problem solving and administrative requests which involve task j alone; by construction $c_{jj}^{1} < 1$;

$\underline{x}_i^{\alpha}$ ∿ a vector of o's and 1's specifying which tasks are included in the i^{th} group, e.g., $x_{ij}^{\alpha} = \begin{cases} 1 & \text{if } j^{th} \text{ task is in the } i^{th} \text{ group} \\ 0 & \text{otherwise} \end{cases}$;

s^{α} ∿ the salary paid an α-level manager; it is assumed that $s^{\alpha+1} > s^{\alpha}$ for all α;

z_i^{α} ∿ the α-level contribution to the i^{th} criterion in the objective function;

$\underline{z}$ ∿ the lexicographic objective function, structured as ranked elements of a vector.

It is now a simple matter to pose the problem. For the sake of brevity, we shall postpone the explanation of each relation until all have been assembled.

Specification of a hierarchy requires that we select integers $\{0 \le x_{ij}^{\alpha} \le 1\}$ to

$$\min_{z_2} \left\{ \min_{z_1} (\underline{z}) \right\} \qquad 1]$$

where

$$z_1 = \sum_{\alpha=1}^{m} s^{\alpha} \underline{e}^{T} \left[(A^{\alpha} \times I) + I \right]_{\text{entier}} \underline{e} \qquad 2]$$

$$z_2 = \sum_{\alpha=1}^{m} s^{\alpha} \underline{e}^{T} (A^{\alpha} \times I) \underline{e} \qquad 3]$$

$$A^{\alpha} = X^{\alpha T} C^{\alpha} X^{\alpha} , \qquad 4]$$

and to satisfy the constraints

$$(A^{\alpha} \times I)\ \underline{e} \le \underline{f} \qquad 5]$$

$$\left\{ \left((C^{\alpha} + I) * \right) \times Y^{\alpha} - Y^{\alpha} \right\} = 0 \qquad 6]$$

$$(X^{\alpha} \underline{e} - \underline{e}) = 0 , \qquad 7]$$

where I is the identity matrix, $\underline{e}$ is a vector of 1's, the symbol (x) denotes

element by element multiplication, $[u]_{entier}$ is a truncation operator yielding the largest integer smaller than u, m is the smallest value of α for which $\mathbb{C}^{\alpha+1}$ is identically zero the symbol (#) is a Boolean operator such that

$$u\# = \begin{cases} 1 \text{ if } u>0 \\ 0 \text{ otherwise} \end{cases} ,$$

$$Y^{\alpha} \equiv X^{\alpha} X^{\alpha^T} , \qquad 8]$$

$$f_1 \equiv \max_{\substack{i=1,n^\alpha \\ j=1,n^\alpha}} \left\{ (\underline{x}_i^\alpha \underline{x}_i^{\alpha^T}) \times D^\alpha \right\} , \qquad 9]$$

and

$$d_{ij}^{\alpha} = d_{ji}^{\alpha} \equiv \left[(c_{ii}^{\alpha} + c_{ij}^{\alpha} + c_{ji}^{\alpha} + c_{jj}^{\alpha}) + 1 \right]_{entier} \qquad 10]$$

The coordination matrix for the next level is obtained from the relation

$$\mathbb{C}^{\alpha+1} = (A^{\alpha} - A^{\alpha} \times \bar{I}) , \qquad 11]$$

and $n^{\alpha+1}$ is merely the number of columns in X^{α}.

As formulated above, the specification of a hierarchy is a nonlinear, two-stage, integer program; however, the sequential structure of the problem suggests that a dynamic programming formulation might be more convenient. The complex - structure of the problem makes it very desirable to obtain the solution heuristically, but this heuristic remains to be developed.

Let's now pause to examine the meaning of each of the relations in the problem statement. The objective function is unusual because of its lexicographic character. It instructs us 1) to find the set of hierarchies requiring the least total supervisory cost, and then 2) to select from that set the hierarchies the ones where the dollar cost spent on coordination is minimal. Note that other properties of the hierarchy may be incorporated into the objective function either as simple, lower order criteria, or as weighted sums.

Equations 2] and 3] specify how the α-level contributes to each criterion. Supervisory cost z_1^{α}, is merely salary times the number of men required to coordinate

the α-level tasks, whereas, coordination cost z_2^α is the product of α-salary and the manpower actually spent in task coordination. The manpower components of z_2^α and z_1^α are, respectively, the actual and the "rounded-up" elements along the main diagonal of A^α.

The three substantive constraints are easily described. Relations 5], 9], and 10] state that the coordination manpower required by a task group cannot exceed the whole number of individuals required to manage that pair of interdependent tasks which need more supervision, as a unit, than any other pair in the group. This condition permits the formation and efficient use of task forces, but at the same time it sharply limits task force size.* The second constraint states that only interdependent tasks may be grouped together, and the third requires that each task must be a member of exactly one task group.

Equation 8] defines a quantity which appears in the constraints, while 11] indicates how to form the matrix of coordination costs that are to be used in constructing the next level of the hierarchy.

Example

Now let's apply the hierarchy rule to a sample problem. We shall portray the task structure as an undirected graph in which nodes are tasks and arcs represent non-zero coordination between pairs of tasks (Fig. 4-1). Nodes and arcs are labeled, respectively, with within-task and between-task coordination requirements, reckoned in men. The salary vector was selected to be representative of the salary structure in a present day industrial firm. Figure 4-2 portrays the optimal and the next best solution, and summarizes cost data.

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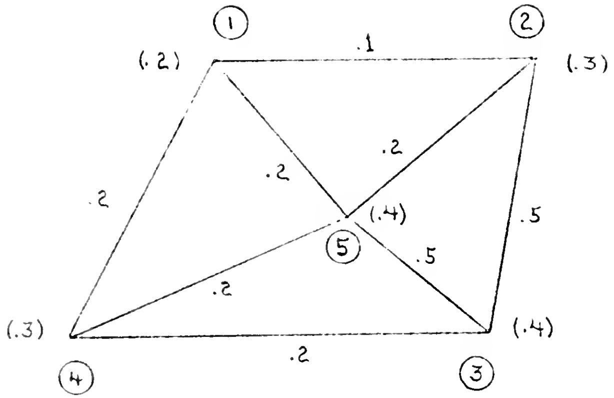
* W.B. Crowston has suggested that a more realistic model would include the cost of coordinating the efforts of task force members. In fact, this is easily done. Moreover, the dependence of task force efficiency on task force size is an empirically researchable issue.



$$\underline{S} = \begin{bmatrix} \$1.0 \times 10^4 \\ 1.4 \\ 2.0 \\ 2.9 \\ 4.25 \end{bmatrix}$$

Figure 4-1 : Task Structure for the Sample Problem.

Optimal Solution:		Next Best Solution:
3.7 men	Coordination manpower required:	3.7 men
5 men	Men used:	5 men
\$ 5.8×10^4	Supervisory cost (z_1):	\$ 5.8×10^4
\$ 4.14×10^4	Coordination cost (z_2):	\$ 4.18×10^4

Figure 4-2: Solutions to the Sample Problem.

5. Model II: Variable Task and Resource Assignments

In the model developed above, coordination cost was assumed known. We shall now extend that model by specifying how shared resources and task precedence structure affect the total cost of a particular organizational design. Thus, to the task group assignments of the previous model, we add two more design elements: 1) the determination of which tasks will use a given group of resources, and 2) the number of resource units required by the design.

However, the kinds of skills required by each task are taken as fixed, and so the quality of the organization's output is held fixed. Because the influence of specialization on quality is not nearly as well understood as its influence on coordination cost, skill mix has been made a parameter rather than a design variable. Thus, to study specialization with this model, one must attribute a skill mix to a specified level of quality, then compare the total cost of the resultant design with the cost of alternate choices for quality and skills.

Now let us generalize the model of section 4. The criterion function is easily modified to include resource cost. We must merely choose resource sizes, resource assignments, and a hierarchy in order to

$$\min_{z_2} \left\{ \min_{z_1} (z_{11} + z_{12}, z_2) \right\} \qquad 12]$$

where

z_{11}~the total salary cost;

z_{12}~the cost of acquiring and maintaining resources;

z_2~the actual dollar cost of coordination

It is a straightforward matter to compute resource cost; however, the impact of resource sharing on coordination cost will be a bit trickier to specify. Define

b_{ik} ~ the amount of the k^{th} resource required by the i^{th} task;

g_{ik} ~ capacity of the i^{th} size unit of the k^{th} resource;

h_{ik} ~ the present value of all cash outlays caused by the acquisition and maintenance of one i^{th} size unit of the k^{th} resource;

w_{ijk} ~ a tensor of 0's and 1's describing which tasks are assigned to the j^{th} group of the k^{th} resource;

$$w_{ijk} = \begin{cases} 1 & \text{if the } i^{th} \text{ task is assigned to the } j^{th} \text{ resource group} \\ 0 & \text{otherwise} \end{cases}$$

u_{ijk} ~ a non-negative integer specifying the number of i^{th} size units assigned to the j^{th} group of the k^{th} resource

The total usage cost is

$$z_{12} = \sum_k \underline{e}^T_k U_k \underline{h}_k \quad , \qquad 13]$$

where the triple subscript notation has been simplified by treating each resource separately.

Of course, each resource must be provided in enough quantity to satisfy the demands of the tasks assigned to the j^{th} group, and each task must be assigned to exactly one group. Thus,

$$W^T_k \underline{b}_k \leq U_k \underline{g}_k \qquad 14]$$

$$(W_k \underline{e}_k - \underline{e}_k) = 0 \qquad 15]$$

with $0 \leq w_{ijk} \leq 1$, integers,

and $0 \leq u_{ijk}$, integers.

We now have the information required to compute the cost of coordinating task pairs. We shall base coordination cost on two factos: 1) task interdependence, and 2) Lawrence and Lorsch's concept of differentiation. Task interdependence is nicely characterized by Thompson's taxonomy of input-output

relations among tasks. He distinguishes three varieties:

1) pooled interdependence, where two tasks have inputs from the same resource but have no output ties;

2) sequential interdependence, where one tasks's output is another's input, and

3) mutual interdependence, where each task of a pair furnishes input to the other.

Thompson did not bother to list the other three members of the mutually exclusive and collectively exhaustive set apparently because all tasks have pooled interdependence in the sense that all share scarce financial resources. However, in the cost computation below, we recognize input sharing and work flow as separate effects.

Differentiation, the second factor in coordination, has been measured along four dimensions: 1) formality of structure, 2) interpersonal orientation 3) time orientation, and 4) goal orientation. As Galbraith implies, the first three dimensions appear to be related strongly to task uncertainty, while the fourth is clearly a beast of a different genre. It seems that a difference in goals would pose a problem both for tasks which are interdependent, and for tasks performed by people who have very different skills. Having already accounted for interdependence, we shall assume that differences in skills make up the rest of Lawrence and Lorsch's goal orientation.

Now we may define the quantities used to compute coordination requirements. Let

$m_i \sim$ the manpower required for the i^{th} task

$\eta_i \sim$ a measure of uncertainty for the i^{th} task; a possible measure is the average of $\|$(predicted task duration) - (actual task duration)$\|$/(actual task duration)

λ_{ij} ~ the fraction of task i's manpower which falls in the j^{th} skill category

q_{ij} ~ the precedence relations between tasks i and j

$$q_{ij} = \begin{cases} 1 & \text{if task i furnishes input to task j} \\ 0 & \text{otherwise} \end{cases}$$

r_{ij} ~ the number of resource units shared by tasks i and j.

Of the many functional forms appropriate for modelling coordination cost, we choose the following because of its simplicity. For within-task coordination,

$$c_{jj}^2 = \left\{ \beta_0 + \beta_1 \eta_j^2 + \beta_2 (1 - \underline{\lambda}_j^T \underline{\lambda}_j) \right\} m_j^2 \qquad 16a]$$

For between-task coordination,

$$\left(\tfrac{1}{2} c_{ij}\right)^2 = \Big\{ \gamma_0 + (\gamma_{11} q'_{ij} + \gamma_{12} q''_{ij} + \gamma_{13} r_{ij} + \gamma_{113} q'_{ij} r_{ij} + \gamma_{123} q''_{ij} r_{ij}) \eta_i \eta_j$$
$$+ (\gamma_{21} q'_{ij} + \gamma_{22} q''_{ij} + \gamma_{23} r_{ij} + \gamma_{213} q'_{ij} r_{ij} + \gamma_{223} q''_{ij} r_{ij})(1 - \underline{\lambda}_i^T \underline{\lambda}_j) \Big\} m_i m_j \qquad 16b]$$

where

$$R = \sum_k W_k W_k^T \qquad 17]$$

$$Q'' = Q \times Q^T \qquad 18]$$

$$Q' = Q - Q' \qquad 19]$$

$$\underline{\lambda}_i = \underline{b}_i / (\underline{b}_i^T \underline{e}) \quad , \qquad i = 1, 2, \ldots, \ell \qquad 20]$$

the β's and γ's are empirically derived constants, and ℓ is the number of human skills used by the organization, with the assumption that the human skills make up the first ℓ columns of the B matrix.

This completes the formulation of the problem which considers the effect of different kinds of interdependence. Equations 2]-20] are required to determine three sets of unknowns: resource sizes, u_{ijk} resource group assignments, w_{ijk}, and task group assignments, x_{ij}.

The solution to this model is strongly influenced by the prior specification of task uncertainty, η; skill mix, λ; task precedence relations, Q, and the possibility of resource sharing, B. Any analysis of the model ought to include a study of how the solution varies with different combinations of these four sets of parameters. The discrete structure of the model makes it much easier to do such an investigation numerically. But this fact should not discourage a more analytic approach to parameter studies.

Before sketching a plan for the empirical test of this model, let's pause a moment to consider the kinds of solutions which the model admits. Clearly, the model will yield a functional organization when the economies from resource sharing outweigh the diseconomies of placing output-related tasks in different groups. And a product organization will result when this balance is struck in the opposite direction. But one may also obtain a matrix organization by including tasks which are solely concerned with the development of human resources.

6. The Next Step

Given the limited empirical data on organization and the complexity of the above formulation, we are reluctant to incorporate more variables into the model. Consideration of specialization and reward structure are possible next steps in the elaboration of the model. However, the addition of specialization must wait until we know more about its influence on quality. And the inclusion of reward structure, though possible and desirable, would add impossible complication to a model which is, perhaps, not now computationally feasible.

In section 3 we suggested that one ought to use a two-stage model in studying design. A start has been made on the static stage. Perhaps it is not premature to begin development of the dynamic stage. A queuing model seems to be a fruitful paradigm. However, the complexity of the situation almost dictates computer simulation, which can be very costly and time consuming. It is only sensible to develop some sort of model before collecting data, but the size of the investment in a simulation counsels for vigorous reality testing very early in the game.

Indeed, for the static model presented here, reality testing should be the next step. In brief, we envisage the following six-step process, extending over a period of 3-4 years:

1) demonstration that elemental tasks can be defined in an actual organization;
2) measurement of model variables determining coordination costs and a direct measurement of the costs themselves;
3) development of an empirical model for coordination cost;
4) computation of the hierarchy based on observed coordination costs and comparison with the existing hierarchy;

5) computation of an organizational design in which resource assignments are variable;

6) replication of steps 1-5) in both a similar and a very different organization.

Step 1) is crucial, for if tasks cannot be defined satisfactorily, the model must be completely reformulated. Interviews with managers at all levels in the chosen organization should provide the inputs, resource requirements, and outputs necessary for task definition. A complete task structure must describe all of the work flows in the organization. Thus, a good test of the task structure is, first, to categorize all jobs flowing into the organization and, second, to verify that the inferred task structure is sufficient to handle the jobs.

The complexity of the hierarchy model suggests that solutions may be difficult to obtain if the number of tasks are of order 100 or more. Of course, one may always reduce the number of tasks by aggregation. But in so doing, one risks ruling out solutions which may be substantially more efficient. A good point of departure would be a 50-task network, with each task definition requiring only moderate aggregation. This implies that the initial research context ought to be an organization of roughly half a thousand people.

As a final word about task definition, we note that about 200 hours of interviewing would be required for task definition in a 500 man organization. This figure is predicated on spending a total of two hours with each of 100 managers.

The measurement of coordination costs would best be done by a longitudinal study in order to assess reliability. We suggest collecting coordination data on 26 pairs of tasks spread as follows among the six categories of interdependence:

		Output Interdependence:			
		None	Sequential	Mutual	Totals
Input Interdependence:	Some	6	6	6	18
	None	---	4	4	8
	Totals	6	10	10	26

Each task pair would be observed during two widely separated weeks. And task members would be queried twice daily on how they spent their time during the preceding period. In between conversations with employees, the research team would gather data on skill mix, non-human resource requirements, and any information pertinent to how the existing hierarchy affects coordination requirements. If data bearing on task uncertainty were not in the organization's records, these data would have to be collected "on-line" during this phase of the study.

As one can see, step two would require a considerable investment of time -- one man-year is probably conservative. However, this time would be well spent because the data collected should provide a solid base for modelling, no matter what the empirical fate of the models in this paper.

Whereas the first two steps were mostly empirical, the third will be mostly analytical. Its goals are 1) a demonstration that a particular set of variables can explain a substantial portion of coordination cost, and 2) a reasoned judgement of the degree to which the existing hierarchy influenced the measured coordination cost. If multiple linear regression is taken as a representative model, the table below indicates that a multiple R^2 of 0.6 ought to satisfy the first requirement.

p-level:	$F_{4,21}$:	R^2:
.05	2.84	0.351
.01	4.37	0.454
.001	6.95	0.570

The empirical portion of step three consists of collecting data for the validation sample. This task should take no more than half a man-year once the form and content of the coordination model have been determined.

Steps four and five are almost self-explanatory. In each case, the optimal organizational design must be carefully compared with the actual design in order to identify and explain all significant differences. We suspect that both the model objective function and the set of constraints may be substantially revised at this point.

Step six is the replication which is often urged but seldom done. Instead of uttering the same old platitudes, we merely note that organizations will demand replication if just the first three steps yield useful results.

Let us now pause briefly to review the logic of the ideas developed here. The paper began with a review of the languages and models pertinent to the design of organization structure. After identifying key structural elements, we suggested that the design problem might be simplified by breaking it into two parts: 1) a dynamic portion which computes coordination cost for a given hierarchy, resource assignments, and other policy variables, and 2) a static portion which determines structural variables for a given network of coordination cost. The remainder of the paper was spent in developing a simple static model and in sketching a plan for its empirical verification.

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